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Letter

Charged-particle multiplicity measurement in proton–proton collisions at $\sqrt{s} = 7$ TeV with ALICE at LHC

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Abstract The pseudorapidity density and multiplicity distribution of charged particles produced in proton–proton collisions at the LHC, at a centre-of-mass energy $\sqrt{s} = 7$ TeV, were measured in the central pseudorapidity region $|\eta| < 1$. Comparisons are made with previous measurements at $\sqrt{s} = 0.9$ TeV and 2.36 TeV. At $\sqrt{s} = 7$ TeV, for events with at least one charged particle in $|\eta| < 1$, we obtain $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta = 6.01 \pm 0.01(\mathrm{stat.})^{+0.20}_{-0.12}(\mathrm{syst.})$. This corresponds to an increase of $57.6\% \pm 0.4\%(\mathrm{stat.})^{+3.6}_{-1.8}\%(\mathrm{syst.})$ relative to collisions at 0.9 TeV, significantly higher than calculations from commonly used models. The multiplicity distribution at 7 TeV is described fairly well by the negative binomial distribution.

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1 Introduction

We present the pseudorapidity density and the multiplicity distribution for primary charged particles[1] from a sample of 3×10^5 proton–proton events at a centre-of-mass energy $\sqrt{s} = 7$ TeV collected with the ALICE detector [1] at the LHC [2], and compare them with our previous results at $\sqrt{s} = 0.9$ TeV and $\sqrt{s} = 2.36$ TeV [3, 4]. The present study is for the central pseudorapidity region $|\eta| < 1$.

In the previous measurements, the main contribution to systematic uncertainties came from the limited knowledge of cross sections and kinematics of diffractive processes. At 7 TeV, there is no experimental information available about these processes; therefore, we do not attempt to normalize our results to the classes of events used in our previous publications (inelastic events and non-single-diffractive events). Instead, we chose an event class requiring at least one charged particle in the pseudorapidity interval $|\eta| < 1$ (INEL $> 0_{|\eta|<1}$), minimizing the model dependence of the corrections. We re-analyzed the data already published at 0.9 TeV and 2.36 TeV in order to normalize the results to this event class. These measurements have been compared to calculations with several commonly used models [5–10] which will allow a better tuning to accurately simulate minimum-bias and underlying-event effects. Currently, the expectations for 7 TeV differ significantly from one another, both for the average multiplicity and for the multiplicity distribution (see e.g. [11]).

2 ALICE detector and data collection

The ALICE detector is described in [1]. This analysis uses data from the Silicon Pixel Detector (SPD) and the VZERO counters, as described in [3, 4]. The SPD detector comprises two cylindrical layers (radii 3.9 and 7.6 cm) surrounding the central beam pipe, and covers the pseudorapidity ranges $|\eta| < 2$ and $|\eta| < 1.4$, for the inner and outer layers, respectively. The two VZERO scintillator hodoscopes are placed on either side of the interaction region at $z = 3.3$ m and $z = -0.9$ m, covering the pseudorapidity regions $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, respectively.

Data were collected at a magnetic field of 0.5 T. The typical bunch intensity for collisions at 7 TeV was 1.5×10^{10} protons resulting in a luminosity around 10^{27} cm^{-2} s^{-1}. There was only one bunch per beam colliding at the ALICE interaction point. The probability that a recorded event contains more than one collision was estimated to be around 2×10^{-3}. A consistent value was measured by counting the

[1] Primary particles are defined as prompt particles produced in the collision and all decay products, except products from weak decays of strange particles.

events where more than one distinct vertex could be reconstructed. We checked that pileup events did not introduce a significant bias using a simulation.

The data at 0.9 TeV and 7 TeV were collected with a trigger requiring a hit in the SPD or in either one of the VZERO counters; i.e. essentially at least one charged particle anywhere in the 8 units of pseudorapidity. At 2.36 TeV, the VZERO detector was turned off; the trigger required at least one hit in the SPD ($|\eta| < 2$). The events were in coincidence with signals from two beam pick-up counters, one on each side of the interaction region, indicating the passage of proton bunches. Control triggers taken (with the exception of the 2.36 TeV data) for various combinations of beam and empty-beam buckets were used to measure beam-induced and accidental backgrounds. Most backgrounds were removed as described in [4]. The remaining background in the sample is of the order of 10^{-4} to 10^{-5} and can be neglected.

3 Event selection and analysis

The position of the interaction vertex was reconstructed by correlating hits in the two silicon-pixel layers. The vertex resolution achieved depends on the track multiplicity, and is typically 0.1–0.3 mm in the longitudinal (z) and 0.2–0.5 mm in the transverse direction.

The analysis is based on using hits in the two SPD layers to form short track segments, called tracklets. A tracklet is defined by a hit combination, one hit in the inner and one in the outer SPD layer, pointing to the reconstructed vertex. The tracklet algorithm is described in [3, 4].

Events used in the analysis were required to have a reconstructed vertex and at least one SPD tracklet with $|\eta| < 1$. We restrict the z-vertex range to $|z| < 5.5$ cm to ensure that the η-interval is entirely within the SPD acceptance. After this selection, 47 000, 35 000, and 240 000 events remain for analysis, at 0.9, 2.36, and 7 TeV, respectively. The selection efficiency was studied using two different Monte Carlo event generators, PYTHIA 6.4.21 [5, 6] tune Perugia-0 [9] and PHOJET [10], with detector simulation and reconstruction.

The number of primary charged particles is estimated by counting the number of SPD tracklets, corrected for:

- geometrical acceptance and detector and reconstruction efficiencies;
- contamination from weak-decay products of strange particles, gamma conversions, and secondary interactions;
- undetected particles below the 50 MeV/c transverse-momentum cut-off, imposed by absorption in the material;
- combinatorial background in tracklet reconstruction.

The total number of collisions corresponding to our data is obtained from the number of events selected for the analysis, applying corrections for trigger and selection efficiencies. This leads to overall corrections of 7.8, 7.2, and 5.7% at 0.9, 2.36, and 7 TeV, respectively.

The multiplicity distributions were measured for $|\eta| < 1$ at each energy. For the 0.9 and 2.36 TeV data we did not repeat the multiplicity-distribution analysis, we used the results from [4] while removing the zero-multiplicity bin. At 7 TeV, we used the same method as described in [4, 13] to correct the raw measured distributions for efficiency, acceptance, and other detector effects, which is based on unfolding using a detector response matrix from Monte Carlo simulations. The unfolding procedure applies χ^2 minimization with regularization [12]. Consistent results were found when changing the regularization term and the convergence criteria within reasonable limits, and when using a different unfolding method based on Bayes's theorem [14, 15].

4 Systematic uncertainties

Only events with at least one tracklet in $|\eta| < 1$ have been selected for analysis in order to reduce sensitivity to model-dependent corrections. However, a fraction of diffractive reactions also falls into this event category and influences the correction factors at low multiplicities. In order to evaluate this effect, we varied the fractions of single-diffractive and double-diffractive events produced by the event generators by ±50% of their nominal values at 7 TeV, and for the other energies we used the variations described in [4]. The resulting contributions to the systematic uncertainties are estimated to be 0.5, 0.3, and 1% for the data at 0.9, 2.36, and 7 TeV, respectively. For the same reason, the event selection efficiency is sensitive to the differences between models used to calculate this correction. Therefore, we used the two models which have the largest difference in their multiplicity distributions at very low multiplicities (see below): PYTHIA tune Perugia-0 and PHOJET. The first one was used to calculate the central values for all our results, and the second for asymmetric systematic uncertainties. The values obtained for this contribution are +0.8, +1.5, and +2.8% for the three energies considered.

Other sources of systematic uncertainties, e.g. the particle composition, the p_T spectrum and the detector efficiency, are described in [4], and their contributions were estimated in the same way. As a consequence of the smaller uncertainties on the event selection corrections the total systematic uncertainties are significantly smaller than in our previous analyses, which use as normalization inelastic and non-single-diffractive collisions. Many of the systematic uncertainties cancel when the ratios between the different energies are calculated, in particular the dominating ones, such as the detector efficiency and the event generator dependence. The systematic uncertainty related to diffractive cross sections was assumed to be uncorrelated between energies.

Table 1 Charged-particle pseudorapidity densities at central pseudorapidity ($|\eta| < 1$), for inelastic collisions having at least one charged particle in the same region (INEL $> 0_{|\eta|<1}$), at three centre-of-mass energies. For ALICE, the first uncertainty is statistical and the second is systematic. The relative increases between the 0.9 TeV and 2.36 TeV data, and between the 0.9 TeV and 7 TeV data, are given in percentages. The experimental measurements are compared to the predictions from models. For PYTHIA the tune versions are given in parentheses. The correspondence is as follows: D6T tune (109), ATLAS-CSC tune (306), and Perugia-0 tune (320)

Energy (TeV)	ALICE	PYTHIA [5, 6]			PHOJET [10]
		(109) [7]	(306) [8]	(320) [9]	
Charged-particle pseudorapidity density					
0.9	$3.81 \pm 0.01^{+0.07}_{-0.07}$	3.05	3.92	3.18	3.73
2.36	$4.70 \pm 0.01^{+0.11}_{-0.08}$	3.58	4.61	3.72	4.31
7	$6.01 \pm 0.01^{+0.20}_{-0.12}$	4.37	5.78	4.55	4.98
Relative increase (%)					
0.9–2.36	$23.3 \pm 0.4^{+1.1}_{-0.7}$	17.3	17.6	17.3	15.4
0.9–7	$57.6 \pm 0.4^{+3.6}_{-1.8}$	43.0	47.6	43.3	33.4

5 Results

The pseudorapidity densities of primary charged particles obtained in the central pseudorapidity region $|\eta| < 1$ are presented in Table 1 and compared to models. The measured values are higher than those from the models considered, except for PYTHIA tune ATLAS-CSC for the 0.9 and 2.36 TeV data, and PHOJET for the 0.9 TeV data, which are consistent with the data. At 7 TeV, the data are significantly higher than the values from the models considered, with the exception of PYTHIA tune ATLAS-CSC, for which the data are only two standard deviations higher. We have also studied the relative increase of pseudorapidity densities of charged particles (Table 1) between the measurement at 0.9 TeV and the measurements at 2.36 and 7 TeV. We observe an increase of $57.6\% \pm 0.4\%(\text{stat.})^{+3.6}_{-1.8}\%(\text{syst.})$ between the 0.9 TeV and 7 TeV data, compared with an increase of 47.6% obtained from the closest model, PYTHIA tune ATLAS-CSC (Fig. 1). The 7 TeV data confirm the observation made in [4, 16] that the measured multiplicity density increases with increasing energy significantly faster than in any of the models considered.

In Fig. 2, we compare the centre-of-mass energy dependence of the pseudorapidity density of charged particles for the INEL $> 0_{|\eta|<1}$ class to the evolution for other event classes (inelastic and non-single-diffractive events), which have been measured at lower energies. Note that INEL $> 0_{|\eta|<1}$ values are higher than inelastic and non-single-diffractive values, as expected, because events with no charged particles in $|\eta| < 1$ are removed.

The increase in multiplicity from 0.9 TeV to 2.36 TeV and 7 TeV was studied by measuring the multiplicity distributions for the event class, INEL $> 0_{|\eta|<1}$ (Fig. 3 left). Small wavy fluctuations are seen at multiplicities above 25. While visually they may appear to be significant, one should note that the errors in the deconvoluted distribution are correlated over a range comparable to the multiplicity resolution and the uncertainty bands should be seen as one-standard-deviation envelopes of the deconvoluted distributions (see also [4]). The unfolded distributions at 0.9 TeV and 2.36 TeV are described well by the Negative Binomial Distribution (NBD). At 7 TeV, the NBD fit slightly underestimates the data at low multiplicities ($N_{ch} < 5$) and slightly overestimates the data at high multiplicities ($N_{ch} > 55$).

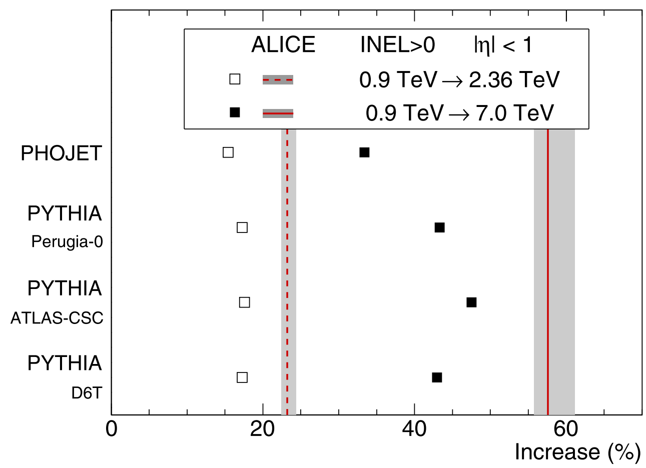

Fig. 1 Relative increase of the charged-particle pseudorapidity density, for inelastic collisions having at least one charged particle in $|\eta| < 1$, between $\sqrt{s} = 0.9$ TeV and 2.36 TeV (*open squares*) and between $\sqrt{s} = 0.9$ TeV and 7 TeV (*full squares*), for various models. Corresponding ALICE measurements are shown with *vertical dashed and solid lines*; the width of *shaded bands* correspond to the statistical and systematic uncertainties added in quadrature

A comparison of the 7 TeV data with models (Fig. 3 right) shows that only the PYTHIA tune ATLAS-CSC is close to the data at high multiplicities ($N_{ch} > 25$). However, it does not reproduce the data in the intermediate multiplicity region ($8 < N_{ch} < 25$). At low multiplicities, ($N_{ch} < 5$), there is a large spread of values between different models: PHOJET is the lowest and PYTHIA tune Perugia-0 the highest.

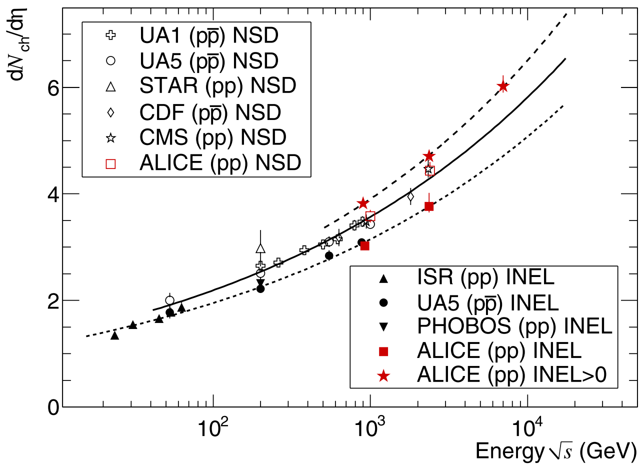

Fig. 2 Charged-particle pseudorapidity density in the central pseudorapidity region $|\eta| < 0.5$ for inelastic and non-single-diffractive collisions [4, 16–25], and in $|\eta| < 1$ for inelastic collisions with at least one charged particle in that region (INEL $> 0_{|\eta|<1}$), as a function of the centre-of-mass energy. The *lines* indicate the fit using a power-law dependence on energy. Note that data points at the same energy have been slightly shifted horizontally for visibility

6 Conclusion

We have presented measurements of the pseudorapidity density and multiplicity distributions of primary charged particles produced in proton–proton collisions at the LHC, at a centre-of-mass energy $\sqrt{s} = 7$ TeV. The measured value of the pseudorapidity density at this energy is significantly higher than that obtained from current models, except for PYTHIA tune ATLAS-CSC. The increase of the pseudorapidity density with increasing centre-of-mass energies is significantly higher than that obtained with any of the models and tunes used in this study.

The shape of our measured multiplicity distribution is not reproduced by any of the event generators considered. The discrepancy does not appear to be concentrated in a single region of the distribution, and varies with the model.

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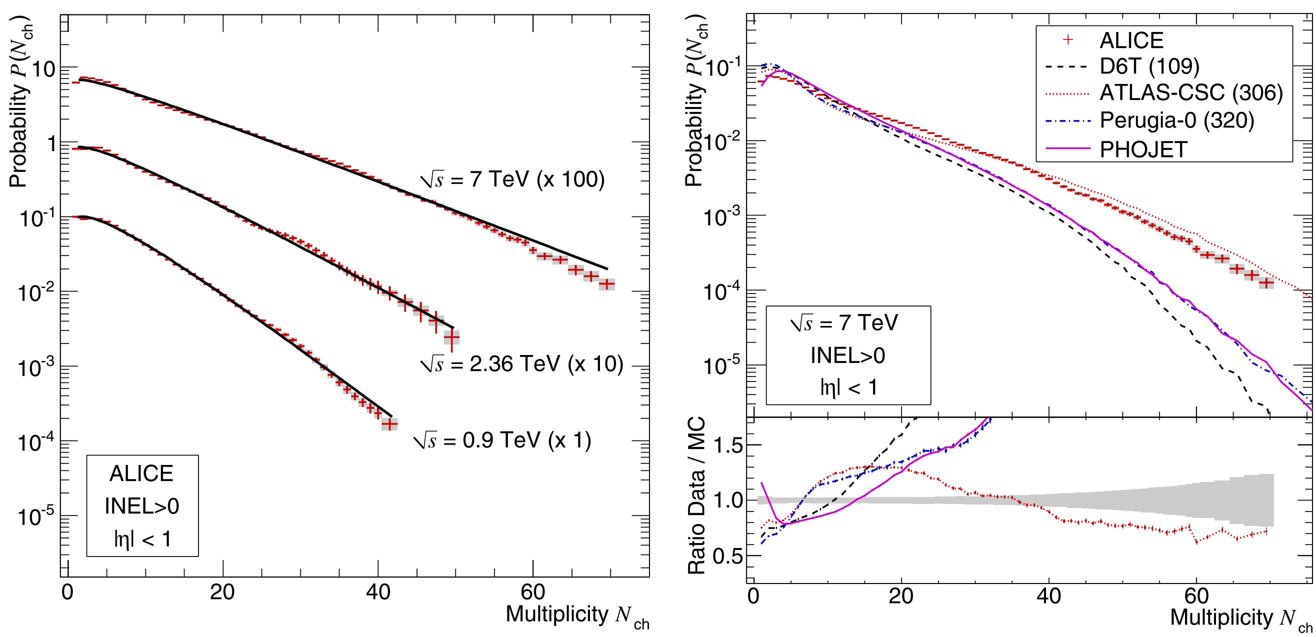

Fig. 3 Measured multiplicity distributions in $|\eta| < 1$ for the INEL $> 0_{|\eta|<1}$ event class. The error bars for data points represent statistical uncertainties, the shaded areas represent systematic uncertainties. *Left*: The data at the three energies are shown with the NBD fits (*lines*). Note that for the 2.36 and 7 TeV data the distributions have been scaled for clarity by the factors indicated. *Right*: The data at 7 TeV are compared to models: PHOJET (*solid line*), PYTHIA tunes D6T (*dashed line*), ATLAS-CSC (*dotted line*) and Perugia-0 (*dash-dotted line*). In the lower part, the ratios between the measured values and model calculations are shown with the same convention. The *shaded area* represents the combined statistical and systematic uncertainties

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